

SPINDLE-SHAPED MICROSTRUCTURES: POTENTIAL MODELS FOR PLANKTONIC LIFE FORMS ON OTHER WORLDS.

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Introduction: Spindle-shaped, organic microstructures ("spindles") are now known from Archean cherts in three localities (Figs. 1-4): The ~3 Ga Farrel Quartzite from the Pilbara of Australia [1]; the older, ~3.3-3.4 Ga Strelley Pool Formation, also from the Pilbara of Australia [2]; and the ~3.4 Ga Kromberg Formation of the Barberton Mountain Land of South Africa [3]. Though the spindles were previously speculated to be pseudofossils or epigenetic organic contaminants, a growing body of data suggests that these structures are *bona fide* microfossils and further, that they are syngenetic with the Archean cherts in which they occur [1-2, 4-10]. As such, the spindles are among some of the oldest-known organically preserved microfossils on Earth.

Moreover, recent $\delta^{13}\text{C}$ study of individual spindles from the Farrel Quartzite (using Secondary Ion Mass Spectrometry [SIMS]) suggests that the spindles may have been planktonic (living in open water), as opposed to benthic (living as bottom dwellers in contact with muds or sediments) [9]. Since most Precambrian microbiotas have been described from benthic, mat-forming communities, a planktonic lifestyle for the spindles suggests that these structures could represent a segment of the Archean biosphere that is poorly known.

Here we synthesize the recent work on the spindles, and we add new observations regarding their geographic distribution, robustness, planktonic habit, and long-lived success. We then discuss their potential evolutionary and astrobiological significance.

Background: Spindle-like structures were first reported by Walsh from the Kromberg Formation of South Africa in 1992 [3]. Fifteen years passed until similar structures were described from other deposits: In 2007, the younger ~3 Ga Farrel Quartzite deposit was documented with many spindle-like forms [1] and then in 2010, similar spindle-shaped structures were reported from the older, Early Archean ~3.3-3.4 Ga Strelley Pool Formation [2], which additionally includes a carbonate facies with some of the oldest reported stromatolites on Earth [11].

The term "spindle" is used for the microstructures in question. All have fusiform or lenticular shapes and most have tails that extend from their major axes. When mapped in 3D, many of these tails are seen to be part of equatorial flanges that encircle the bodies of the structures [5, 7]. The spindles also are characterized by

reticulate, internal carbonaceous networks; occasional vacuole-like cavities; and occasional internal carbonaceous spheroids [1, 5, 8].

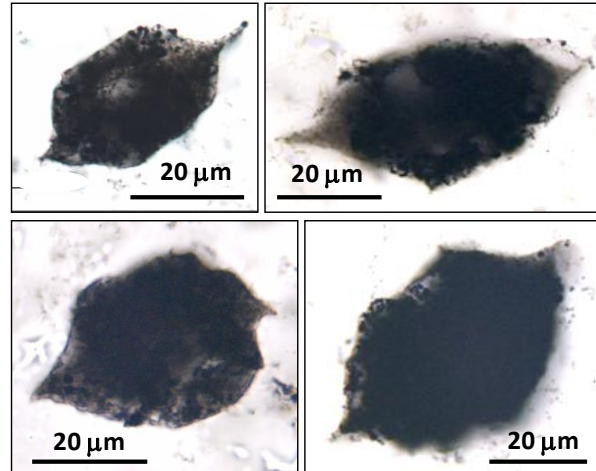


Fig. 1. Optical photomicrographs (transmitted light) of spindles in thin sections of chert from the Farrel Quartzite.



Fig. 2. Optical photomicrograph (transmitted light) of spindles in thin section of chert from the Farrel Quartzite.

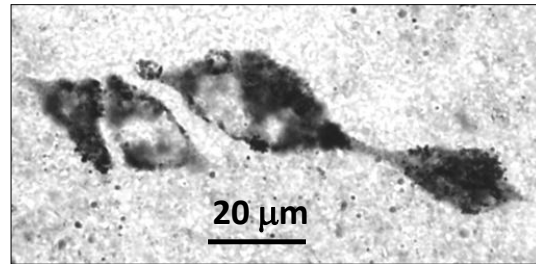


Fig. 3. Optical photomicrograph (transmitted light) of spindles in thin section of chert from the Strelley Pool Fm.

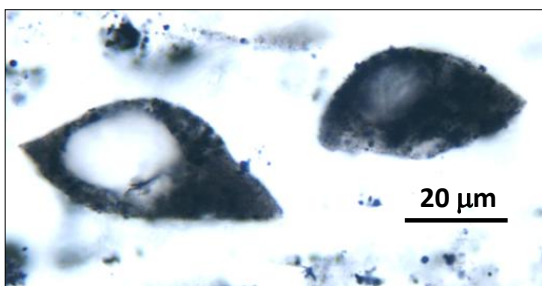


Fig. 4. Optical photomicrograph (transmitted light) of spindles in thin section of chert from the Kromberg Fm.

The spindles occur individually and in groups or chains of a few to several individuals (Figs. 1-4). They are commonly ~20-80 μm long by ~15-30 μm wide (though there are differences in size ranges of the populations from the three deposits). Hundreds of examples have been documented in the Farrel Quartzite and Strelley Pool Fm. (1-2, 5-6), and the spindles are commonly found in association with other structures thought to be remnants of ancient organisms, including films, threads, and clusters of spheroids [1].

Discussion: The spindles are unusually large for such ancient forms, particularly those preserved in chert (though see [12] for report of large spheroids in 3.2 Ga clastic rocks). It is because of the large size of the spindles, coupled with their unusual morphology, that their origin has been controversial. Early thoughts included considerations that the spindles might be 1) pseudofossils formed by accumulation of organic debris around crystal surfaces, 2) organic contaminants introduced into the cherts epigenetically, 3) fluid inclusions, or 4) true microfossils of Archean microbes [1, 3]. Extensive studies since 2007 have eliminated most of the uncertainty: Raman spectroscopy shows that the spindles are carbonaceous [2, 5, 10]; NanoSIMS illustrates that the bounding carbonaceous material is elementally identical to, and contiguous with, material making up the internal networks (arguing against an origin from organic accumulations on crystal surfaces) [8]; SIMS-derived $\delta^{13}\text{C}$ evaluation demonstrates that organic matter of the Farrel Quartzite spindles is isotopically distinct from that of adjacent organic fragments (supporting conclusions from NanoSIMS that the spindles were not formed by organic debris collecting on mineral grains) [9]; SIMS-derived H/C and $\delta^{13}\text{C}$ analyses, Raman spectroscopy, and petrography of Strelley Pool organic constituents (including spindles) suggest that these spindles are both biogenic and indigenous [10], and morphological, taphonomic, petrographic, and palynological studies support the interpretation that the spindles are *bona fide* microfossils [1, 2, 4-7], syngenetic with the Archean cherts in which they are found [5].

SIMS-derived $\delta^{13}\text{C}$ values of Farrel Quartzite samples suggest that the spindles were planktonic [9].

A planktonic interpretation would be consistent with the large, near equant shapes of the spindles and with their equatorial flanges and vacuole-like cavities (which are similar to structures that control buoyancy in some modern plankton). The occurrence of spindles within the cherts may also support a planktonic interpretation, as the spindles commonly are dispersed without preferred orientation in regions of chert lacking the organic laminae that are typically associated with benthic microbial mats.

Finally, the spindles appear to be robust. Their walls preserve sufficient organic carbon for repeated SIMS $\delta^{13}\text{C}$ analyses whereas earlier attempts (by C.H.H.) to analyze SIMS $\delta^{13}\text{C}$ of different Archean microfossils were unsuccessful due to the limited quantities of preserved carbon in those structures.

Evolutionary/Astrobiological Significance: The recent studies argue that the spindles are remnants of Archean microorganisms that were widespread in the biosphere of the early Earth. The distribution of the spindles in Australia and South Africa is notable. The spindles may have expanded geographically early in Earth history because of their planktonic habit (which could have facilitated their dispersal in Archean oceans), their robustness, a paucity of competitors on a young planet, and the possibility that the configuration of Archean land masses was such that the Pilbara and Barberton Mountain Land were closer to one another than they are today. The fact that similar spindle-like structures occur in sediments ranging in age from ~3.4 to 3 Ga suggests that the organisms they represent were long-lived and successful, flourishing on the Earth for a minimum of 400 million years.

Because of the great age of the spindles plus their apparent robustness, planktonic habit, and long-lived success, it is plausible that, through parallel evolution, similar forms could have evolved on other worlds. Accordingly, the spindles may exemplify an architecture that would be anticipated for early life forms on planets in habitable zones where modeling additionally predicts an abundance of liquid water.

Path Forward: Ongoing work is aimed at addressing the significance, habitat, and interrelationships of the Archean spindles using SIMS-derived $\delta^{13}\text{C}$ plus morphological, petrographic, and geochemical analyses.

References: [1] K. Sugitani et al. (2007) *Prec. Res.* 158, 228-262. [2] K. Sugitani et al. (2010) *Astrobiology* 10 (9), 899-920. [3] M. Walsh (1992) *Prec. Res.* 54, 271-293. [4] M. Walsh et al. (in prep). [5] Sugitani et al. (2009) *Prec. Res.* 173, 50-59. [6] K. Sugitani et al. (2009) *Astrobiology* 9, 603-615. [7] K. Grey, K. Sugitani (2009) *Prec. Res.* 173, 60-69. [8] D. Oehler et al. (2010) *Astrobiology* 10, 413-424. [9] C. House et al. (2013) *Geology* 41 (6), 651-654. [10] K. Lepot et al. (2013) *GCA* 112, 66-86. [11] A. Allwood et al. (2006) *Nature* 441, 714-718. [12] E. Javaux et al. (2010) *Nature* 463, 934-938.